

Ion Charge States in Halo CMEs: What can we Learn about the Explosion?

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ABSTRACT

We describe a new modeling approach to develop a more quantitative understanding of the charge state distributions of the ions of various elements detected in situ during halo Coronal Mass Ejection (CME) events by the Advanced Composition Explorer (ACE) satellite. Using a model CME hydrodynamic evolution based on observations of CMEs propagating in the plane of the sky and on theoretical models, we integrate time dependent equations for the ionization balance of various elements to compare with ACE data. We find that plasma in the CME “core” typically requires further heating following filament eruption, with thermal energy input similar to the kinetic energy input. This extra heating is presumably the result of post eruptive reconnection. Plasma corresponding to the CME “cavity” is usually not further ionized, since whether heated or not, the low density gives freeze-in close to the Sun. The current analysis is limited by ambiguities in the underlying model CME evolution. Such methods are likely to reach their full potential when applied to data to be acquired by STEREO when at optimum separation. CME evolution observed with one spacecraft may be used to interpret CME charge states detected by the other.

Subject headings: Sun: solar wind — atomic processes — plasmas — waves

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1. Introduction

Coronal Mass Ejections (CMEs) represent perhaps the most extreme manifestation of solar activity. Of order 10^{16} g of plasma is expelled at speeds of several hundred m s^{-1} to in excess of one thousand km s^{-1} . Such speeds are frequently super-Alfvénic with respect to the ambient solar wind, and the shocks driven by CME events can be efficient accelerators of energetic particles, constituting the main radiation hazard for space-borne instrumentation. The spectacular nature of the phenomenon, and its relevance to space based technology, have spawned much theoretical and observational work with the ultimate goal of understanding CMEs sufficiently deeply to enable the forecasting of such events, in a discipline that has become known as “space weather”.

The interplanetary manifestation of CMEs (ICMEs) embedded in the solar wind can exhibit a variety of signatures in the magnetic field, solar wind speed and density profiles, proton thermal properties, elemental and ionic composition, and the presence of energetic particles (see Zurbuchen and Richardson, 2006 for more detail). Of particular interest here are the ionic charge states observed in the solar wind during ICMEs. Unlike many plasma properties, the charge states are determined within 4 solar radii and remain unchanged as they expand further into the heliosphere. This property makes them an important signature of the eruption process close to the Sun. A large body of literature exists highlighting the rich data sets which detail the unique charge composition observed within ICMEs (e.g. Zurbuchen and Richardson 2006, Zurbuchen et al. 2004, Lepri and Zurbuchen 2004, Lepri et al. 2001, Henke et al. 2001, Gloeckler et al. 1998, Henke et al. 1998, Galvin & Gloeckler 1997, Reinard 2005).

While a number of studies have examined the existing solar wind composition data and made inferences on freeze-in temperatures based on computed ionization distributions appropriate to coronal equilibrium, in this paper we commence time-dependent modeling of the ion charge state distributions of various elements to draw quantitative conclusions regarding the thermal energy input and initial conditions in the corona during the CME eruption. Using current ionization-recombination calculations and a simple model for the spatial and temperature evolution of the CME plasma we attempt to reproduce the charge states detected *in situ* by instruments on the Advanced Composition Explorer (ACE) spacecraft. In order to provide some context for our work, we first review the status of theory and observation for CMEs. Following this, we describe our modeling approach in some detail, and apply our methods to a sample of ICMEs detected ACE, which were chosen to provide a variety of ICME speeds and charge state distributions.

2. CME Theory and Observation: Current Status

CMEs were first discovered during the Skylab era (Gosling et al. 1974), and a “halo CME” (i.e. an Earth directed event) was first detected by the P78-1 coronagraph (Howard et al. 1985). Since the 1995 launch of SOHO, they are now routinely observed and studied by the Extreme Ultraviolet Imaging Telescope (EIT) and Large Angle Spectroscopic Coronagraph (LASCO) instruments (e.g. Dere et al. 1997). LASCO white light observations are sensitive to photospheric radiation Thomson scattered by free electrons in the corona. Three nested coronagraphs provided coverage between 1.5 and 30 R_{\odot} heliocentric distance, reduced to 2.5 - 30 R_{\odot} following the 1998 demise of C1. EIT records images in narrow EUV wavebands emitted closer to the solar surface, and allows investigations of the coronal precursor and response to the CME eruption. This instrumentation provides the context for the observations of most importance in this work, those of particle charge states and masses detected *in situ* at the L1 Lagrange point by mass and charge to mass spectrometers on board the Advanced Composition Explorer (ACE). We use Level 2 data supplied by the ACE Science Center from the SWICS/SWIMS (Solar Wind Ion Composition Spectrometer/Solar Wind Ions Mass Spectrometer) and SWEPAM (Solar Wind Electron Proton Alpha Monitor) instruments.

For our purposes, the most important feature of CMEs is their rate of expansion and acceleration close to the Sun. For the time being, we are not able to simultaneously observe the expansion rate of a CME for which we also detect the particle emission, and must estimate the velocity profile of a halo CME from observations of other CMEs propagating in the plane of the sky. Happily, these frequently follow a similar form (Zhang et al. 2001, 2004; Zhang & Dere 2006). Observationally, CME evolution can be divided into three phases. An initial phase of expansion at approximately constant velocity in the range 10-100 km s⁻¹, is called the “initiation phase”, during which the flux rope rises to a height of about 1.5 R_{\odot} . This is followed by the “acceleration phase”. During this period, the CME undergoes a roughly constant acceleration up to its final speed, between a few 100 km s⁻¹ to a few 1000 km s⁻¹ for the fastest CMEs. Typically this final speed is achieved around 5-10 R_{\odot} . Lastly, the “propagation phase” with essentially constant velocity transports the CME to 1 AU and beyond. These features are also apparent in theoretical work. In the breakout model (Antiochos 1998; Antiochos et al. 1999; DeVore & Antiochos 2000; Aulanier et al. 2002), the initiation phase corresponds to the initial shearing of the magnetic field lines closest to the filament channel in an overlying arcade of loops. As the filament rises and reconnection commences underneath it, the acceleration phase begins, typically at 1.5 R_{\odot} (see Fig. 1 in Lynch et al. 2004). In the breakout model, post-eruptive reconnection beneath the erupting filament is not strictly necessary for an explosion to occur, though reconnection above the filament is required. There appears to be no clear event to signal the end of the acceleration

phase, though clearly a CME cannot continue accelerating forever. Analytic models of CME eruptions (Lin & Forbes 2000) can also give similar height-time and velocity-time profiles. Again, the transition from the initiation phase to the acceleration phase corresponds to the formation of a current sheet below the flux rope. The resulting analytic solutions for the height and velocity of the reconnection-driven flux rope do indeed show an approximately constant acceleration phase, followed by a roughly constant velocity phase, at least for models with relatively high reconnection rates producing fast CMEs. Some deceleration may also occur during the propagation phase.

The morphology of the erupting CME plasma, while generally quite variable, shows a regular pattern of features for flux rope or magnetic cloud CMEs, which are thought to be associated with erupting prominences, and which will be the focus of most of our modeling using the event list of Lynch (2006). The CME front (a shock front in CMEs fast enough to drive a shock) encloses a “cavity” region, presumably a region of strong magnetic field comprising the flux rope (Lynch et al. 2004). Towards the rear of the erupting plasma is the CME “core”, and region with density perhaps a factor of 10 higher than in the cavity. This region possibly has an origin as the cold prominence material. Reconnection above the erupting filament in the breakout model would be expected to heat the cavity plasma, if anything. Unfortunately the cavity plasma is usually too rarefied for any heating to be visible in the detected ion charge states. Reconnection behind the eruption (e.g. Riley et al. 2002, 2007), for example to form postflare loops, will most likely heat the core material, where the density is high enough that increased ionization can set in before freeze-in. Kumar & Rust (1996) model a lower velocity flux rope eruption, making the assumption that magnetic helicity is conserved during the process. They find that the magnetic energy of the flux rope must decrease, and that not all of this energy can be converted into kinetic energy of the expanding plasma, some must go to heat, though the exact form and location of the magnetic energy dissipation is not specified.

The flux rope may also be distorted during transit to 1 AU. Riley & Crooker (2004) model the effects of spherical expansion and the effect of pressure gradients between the CME plasma and the ambient solar wind. The flux rope may expand substantially in latitude. Schmidt & Cargill (2001) consider the case of the flux rope propagating in the velocity shear layer between the fast and slow solar wind, and find that the magnetic topology may be changed by reconnection. In this way, plasma from the CME “core” and “cavity” regions may become mixed together before *in situ* detection at 1 AU by ACE.

3. Modeling Approach

Our simulations follow the evolution of high density core and lower density cavity material for a CME. The ionization balance for the two components are followed separately starting from coronal or flare temperatures allowing for heating during the acceleration phase of the CME evolution, particularly of the core material. Various parameters listed below are adjusted to match the velocity, plasma density, and most importantly the charge state distributions of O, Si and Fe observed by ACE for a small selection of CMEs. Given the degeneracies in parameter space that will be removed by the simultaneous observation of CMEs from face-on and edge-on viewpoints with STEREO, our primary intent at this time is to illustrate that the CME charge states can be successfully modeled under reasonable assumptions.

3.1. Charge State Evolution

Our approach to modeling CME charge states is to follow the behavior of the ionization balance of a Lagrangian plasma packet, using an analytic prescription for the hydrodynamic or magnetohydrodynamic evolution. We use an adaptation of the BLASPHEMER (BLAST Propagation in Highly EMitting EnviRonment)¹ code (Laming & Grun 2002, 2003; Laming & Hwang 2003; Laming 2004), which follows the time dependent ionization balance and temperatures of a Lagrangian plasma parcel as it expands in the solar wind. The initial conditions are set by assuming ionization equilibrium at an electron temperature of $1 - 3 \times 10^6$ K appropriate for coronal plasma.

The density n_{iq} of ions of element i with charge q is given by

$$\frac{dn_{iq}}{dt} = n_e (C_{ion,q-1} n_{i,q-1} - C_{ion,q} n_{iq}) + n_e (C_{rr,q+1} + C_{dr,q+1}) n_{i,q+1} - n_e (C_{rr,q} + C_{dr,q}) n_{iq} \quad (1)$$

where $C_{ion,q}$, $C_{rr,q}$, $C_{dr,q}$ are the rates for electron impact ionization, radiative recombination and dielectronic recombination respectively, out of the charge state q . These rates are the same as those used in the recent ionization balance calculations of Mazzotta et al. (1998), using subroutines kindly supplied by Dr P. Mazzotta (private communication 2000), with the following updates. Dielectronic recombination from H- to He-like and from He- to Li-like are taken from Dasgupta & Whitney (2004). Dielectronic recombination for the successive isoelectronic sequences Li-, Be-, B-, C-, N-, O-, and F-like are taken from Colgan, Pindzola, & Badnell (2004), Colgan et al. (2003), Altun et al. (2004), Zatsarinny et al. (2004a), Mitnik & Badnell

¹The name gives away its origin in modeling laboratory and astrophysical shock waves.

(2004), Zatsarinny et al. (2003), and Gu (2003) respectively. Additionally, dielectronic recombination from Ne- to Na-like and from Na- to Mg-like are taken from Zatsarinny et al. (2004b) and Gu (2004). We also take dielectronic recombination rates for Fe^{13+} from Badnell (2006). The electron density n_e is determined from the condition that the plasma be electrically neutral. The ion and electron temperatures, T_{iq} and T_e are coupled by Coulomb collisions by

$$\frac{dT_{iq}}{dt} = -0.13n_e \frac{(T_{iq} - T_e)}{M_{iq}T_e^{3/2}} \frac{q^3 n_{iq}/(q+1)}{\left(\sum_{iq} n_{iq}\right)} \left(\frac{\ln \Lambda}{37}\right) \quad (2)$$

and

$$\frac{dT_e}{dt} = \frac{0.13n_e}{T_e^{3/2}} \sum_{iq} \frac{(T_{iq} - T_e)}{M_{iq}} \frac{q^2 n_{iq}/(q+1)}{\left(\sum_{iq} n_{iq}\right)} \left(\frac{\ln \Lambda}{37}\right) - \frac{T_e}{n_e} \left(\frac{dn_e}{dt}\right)_{ion} - \frac{2}{3n_e k_B} \frac{dQ}{dt}. \quad (3)$$

Here M_{iq} is the atomic mass of the ions of element i and charge q in the plasma, and $\ln \Lambda \simeq 28$ is the Coulomb logarithm. The term in dQ/dT represents plasma energy losses due to ionization and radiation. The term $-(T_e/n_e)(dn_e/dt)_{ion}$ gives the reduction in electron temperature when the electron density increases due to ionization. Recombinations, which reduce the electron density, do not result in an increase in the electron temperature in low density plasmas, since the energy of the recombined electron is radiated away (in either radiative or dielectronic recombination).

3.2. Hydrodynamic Evolution

We based our model CME evolution on the phenomenology described in section 2, of an initiation, acceleration and propagation phase, to use the terminology of (Zhang et al. 2001, 2004). Plasma starts at $1.5R_\odot$ moving at an initial velocity, v_i , between 10 and 100 km s^{-1} , i.e. as it moves from the “initiation” to the “acceleration” phase. The initial electron density, is taken to be either near 10^8 cm^{-3} or a factor of 10 lower, corresponding to plasma in the CME “core” or “cavity” respectively. An acceleration, a , of 0.1–0.5 km s^{-2} is chosen so that the CME reaches its final coasting velocity, v_f , at a heliocentric distance of 3–10 R_\odot (R_c). The density is assumed to fall off as $1/r^{(2+v_A/(v_A+v_r))}$, where v_A is the coronal Alfvén speed and v_r is the CME expansion speed. This form, with a suitable choice for v_A ($\sim 1000 \text{ km s}^{-1}$), gives an initial superradial expansion as the CME expands laterally, going over to a $1/r^2$ form at large distances from the Sun. The Alfvén speed, v_A , is assumed to vary approximately as $1/r^{1/3}$ or $n_e^{1/6}$, coming from the approximate relations $B \propto 1/r^{4/3}$ (the geometric mean of $B_r \propto 1/r^2$ and $B_\theta \propto B_\phi \propto 1/r$) and $\rho \propto 1/r^2$. Mann et al. (2003) give a more detailed account of the variation of the Alfvén speed with radius in the quiescent solar

corona above an active region. However our simpler form gives a density dependence on radius which matches very well with the various plots in Lynch et al. (2004), and is certainly adequate for our needs.

For simplicity we assume the core and cavity differ in density by a factor of 10, but contribute roughly equal amounts of material by mass and undergo the same velocity and expansion evolution. Their electron temperatures at “initiation” are either assumed to be the same or the cavity temperature is held lower, in the range of typical coronal, rather than flare, temperatures. Subsequent heating of the higher density core plasma during the acceleration phase is explored assuming a heating rate for the CME plasma proportional to the rate of kinetic energy increase, i.e. a constant fraction QE/KE during the acceleration up to v_f . Here we assume that all particle species are heated equally, but our models are only sensitive to the electron temperature. Hence depending on how the magnetic reconnection partitions energy between electrons and ions, and whether the heat input is constant during the acceleration phase, different CME energy budgets may result. Having the heating be proportional to the acceleration during the acceleration phase is one choice which allows for particularly easy comparisons of the energetics. However, we cannot distinguish between this scenario and impulsive heating to high temperatures ($2\text{--}3 \times 10^7 \text{K}$) during the initiation phase (with insufficient time to reach ionization equilibrium). The observation of high charge states simply requires that high temperatures be reached while the density is still high enough to allow for significant ionization of the high Z elements. Such heating was not further explored for the cavity material simply because at those densities it would have little or no impact on the ionization state which freezes in well below $2R_\odot$.

4. Modeling a Sample of ACE Coronal Mass Ejections

A sample of 6 ICME events was selected from a catalog of magnetic cloud events by Lynch (2006), supplemented by two more events from the survey of Ugarte-Urra et al. (2007), all listed in Table 1. Listed here are the average, standard deviation and maxima of the He velocity, proton density and the abundance ratios of He/O and Fe/O as measured at ACE with the SWICS/SWIMS and SWEPAM instruments (proton density). The abundance ratios seen were generally typical for coronal material except for the Halloween 2003 event which shows significantly enhanced Fe/O. He/O ratios on the other hand, especially in the faster CMEs, are more typical of the chromospheric value of ~ 130 , or of that found in flares (Feldman et al. 2005), and not the lower values found elsewhere in the solar wind and corona (e.g. Laming & Feldman 2003; Kasper et al. 2007). The observed velocity may be considered a lower limit, since deceleration is likely to have occurred in transit to 1 AU,

however our simulation results were relatively insensitive to the final velocity. The proton density at 1 AU can be compared to the electron density at $10R_{\odot}$ by multiplying by a factor of ~ 400 for the $1/r^2$ density fall off and another factor of 1.2—1.6 for the proton to electron density ratio. We expect the measured proton density to reflect some combination of core and cavity material.

Examples of successful CME models for the chosen events are listed in Table 2 in order of increasing velocity. The dominant charge states for each model are listed in order of abundance composing a total charge fraction of at least 0.8. These are representative of the charge states observed at ACE, which, however, did vary over the course of an ICME event. Examples of the observed charge states at different slices in time, the final modeled charge states of the combined core and cavity plasma, and the initial evolution of ion fractions in the core material are shown for the 2001 doy 351 ICME and the Halloween 2003 events in figures 1, 2, and 3 and 4, 5, and 6, respectively. The model solution for any given event is not unique, and we used this freedom to choose an ensemble that exhibits the range of behavior possible and the effect of any given parameter. To begin modeling, the parameters of the initial velocity, density, acceleration and lateral expansion (via the Alfvén speed) are chosen to match the velocity and plasma density of the CME in question as measured by ACE. The model acceleration and expansion also agree well with observational results in Vourlidas et al. (2003) and Thernisien et al (2006) for the region behind the forward shock. Both theoretical models and observations of CMEs in the plane of the sky show a high density core of plasma surrounded by a lower density cavity. The bimodal charge distribution of both Fe and Si in most of the CMEs considered here is naturally concordant with a mixing of cavity and core material during the CME flux rope passage to 1 AU after freeze-in has occurred.

In 5 out of 8 sample CMEs the dominant Fe charge states are Neon-like ($16+$) or higher, indicating that high temperatures, comparable to flares ($\sim 10^7\text{K}$), are involved. Starting the plasma from this temperature and allowing the ions to recombine as they expand can often account for the Fe ionization balance, with peaks around Fe^{16+} and Fe^{8+} (the Ne-like and Ar-like charge states, which have small recombination rates to the next charge states down, hence population “bottlenecks” here). However the lower-Z elements place a limit on the maximum starting temperature (at least if assuming ionization equilibrium in the seed plasma). Above $\sim 2.5 \times 10^6\text{K}$ O would be mainly O^{8+} instead of O^{7+} and O^{6+} as observed and would not recombine significantly during the CME evolution. Evidently plasma must start out much cooler, and be further heated as the CME accelerates. While various possibilities exist among CME models regarding the role of reconnection in initiating or accelerating the CME, nearly all of them require reconnection to produce the post-eruptive arcades of magnetic loops (e.g. Riley et al. 2007). We follow Lepri & Zurbuchen (2004) and argue that this reconnection must also heat the CME plasma and that this is the cause for the high charge states. Of

the 3 events without a peak at high charge states in Fe, in ICMEs 2003 doy 129 and 2001 doy 351 the broad distribution of both Si and Fe does require some heating. In the slowest event that shows no elevated charge states, 2002 doy 173, no heating is required but neither can it be excluded.

Finally, in Table 2 we also enter for some CMEs the velocity of the CME front as deduced from SOHO/LASCO height-time observations², and the acceleration necessary to produce this velocity at the heights observed. The variation in heating rate as a multiple of the CME kinetic energy is surprisingly small. Only for the extreme 2003 October 29 (doy 302) event is the modeling really sensitive to this behavior. We caution that the height-time observations give the velocity of the CME front, not the expansion velocity of the flux rope or magnetic cloud containing the ejecta, and that it is not possible in all cases to unambiguously identify the disk event that gave rise to the observed ICME.

5. Discussion and Conclusions

Our basic result, that the erupting CME plasma must be further heated as it expands, is not entirely unexpected from theoretical considerations. Kumar & Rust (1996) model the evolution of an expanding flux rope. For a ratio of initial gravitational energy to magnetic energy in the flux rope of 0.22, they find that between 0.58 and 0.78 of the initial magnetic energy is converted to forms of energy other the gravitational potential energy and kinetic energy of the plasma, i.e., is available for plasma heating or the generation of radiation or plasma waves. The maximum amount of magnetic energy that can go to plasma kinetic energy is 0.38, so *at least* 1.5 times the kinetic energy in their model must appear as heat.

Kumar & Rust (1996) do not specify the precise mechanism by which the magnetic energy is converted into other forms, arguing as they do simply from conservation of total energy and magnetic helicity. On the other hand, Lin & Forbes (2000) considered in a little more detail the expulsion of a current carrying flux rope, paying more attention to the initial quasi-equilibrium configuration and specifying magnetic reconnection as the mechanism of releasing magnetic energy. Their treatment of reconnection assumes, somewhat arbitrarily, that all magnetic energy destroyed reappears as plasma kinetic energy, and hence the CME speed in their model is therefore an overestimate. However they do comment that previous numerical simulations by Forbes (1991) show that “only about half of the released magnetic energy is actually converted into the kinetic energy of the flux rope; the other half goes into heating, radiation, and the generation of plasma waves”. Therefore these authors also

²using the CME catalog at <http://cdaw.gsfc.nasa.gov/CMElist>

suggest that an amount of thermal energy, similar to the kinetic energy of the CME, should be generated, and that this should result from magnetic reconnection. However magnetic reconnection does not power the CME. It is accelerated by $\mathbf{j} \times \mathbf{B}$ forces within the flux rope, and reconnection eliminates magnetic field that holds the flux rope down in the initial quasi-equilibrium configuration.

Magnetic reconnection plays a similar role in the breakout model of CMEs (Antiochos 1998; Antiochos et al. 1999; DeVore & Antiochos 2000; Aulanier et al. 2002). Again, it plays the role of destroying magnetic field that otherwise holds the CME plasma in equilibrium. Once this magnetic field is eliminated, the CME is powered by the magnetic field below, stressed by shear motions either side of the neutral line. Reconnection at this lower site, which forms postflare loops, has nothing to do with allowing the CME to erupt, but may still be a heat source for the CME plasma. Hence in both the Lin & Forbes (2000) flux rope model and in the breakout scenario, no strong prediction exists for how much plasma heating should be expected as a function of CME kinetic energy, though simple estimates of the magnetic energy destroyed in these cases are indeed of the right order of magnitude to supply the amount of heat we see in the charge state distributions. Shiota et al. (2005) give a numerical simulation of a flux rope ejection, and stress the role of the slow mode MHD shock in providing heat to the flux rope plasma.

Our estimates of post-eruptive heating are of course sensitive to the electron heating only, although we assume that all plasma particles are similarly heated. Observations of post eruption electron acceleration are reported by Klassen et al. (2005) for the 2003 October 28 event. Type III, II, and IV radio bursts are detected coincident with the soft X-ray rise of the flare. Following that, an impulsive electron event in the energy range 0.027-0.182 MeV and a gradual electron event with energies 0.31-10.4 MeV were detected by WIND-3DP and SOHO/COSTEP, with a total duration of about 30 minutes following CME onset, by which time the CME front had expanded to about $6R_{\odot}$. The total energy in these accelerated electrons is significantly less than the heating requirements we give in Table 2 (Mewaldt et al. 2005), however the timescale following eruption is commensurate with our requirements. The expansion velocity of the CME front given by Klassen et al. (2005), derived from height-time measurements from SOHO/LASCO observations, is also higher than the CME velocity we give in Table 2, and requires a significantly larger acceleration to achieve this velocity by about $5.8R_{\odot}$ where it was first observed by SOHO/LASCO. We have experimented with different accelerations, and find that for this particular CME, for accelerations above $1\text{-}2 \text{ km s}^{-2}$, it is impossible to match the observed charge states for any post eruption heating rate. We emphasize that we are principally interested in the plasma in the CME “core”, and that the expansion of this material might not be well represented by the SOHO/LASCO observations of the CME front. Additionally, this was a halo CME, so

SOHO/LASCO observes the CME front off to one side of the main eruption. We anticipate that such ambiguities will be substantially resolved with the advent of STEREO data.

Similar conclusions to ours about the thermal energy input to CMEs have been reached from analysis of ultra-violet spectra taken by SOHO/UVCS. Akmal et al. (2001) studied a 480 km s^{-1} CME observed on 1999 April 23, and found a thermal energy comparable to the bulk kinetic energy of the plasma. Ciaravella et al. (2001) gave similar results for the 260 km s^{-1} 1997 December 12 CME, while Lee et al. (2007) studied the 2001 December 13 event, also examined by Ugarte-Urra et al. (2007), and included in our Table 2. None of these appear in the magnetic cloud event list of Lynch (2006).

To summarize, our work on interpreting charge state distributions for the ions of various elements support previous ideas in the literature that CME plasma continues to be heated as the eruption proceeds. A future quantitative study of this may yield novel insights into the mechanism(s) of explosion, especially because the charge states are formed by processes close to the Sun, and are then transported unchanged to 1 AU.

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Table 1: ICME Observations

Year	Start (doy)	$v_{\text{He}^{++}}$ (km s $^{-1}$) ^a		ρ_{H^+} (cm $^{-3}$)		He/O ^b		Fe/O	
		ave.	max	ave.	max.	ave.	max.	ave.	max.
2002	173	416 \pm 19	464	4.4 \pm 1.1	6.9	80 \pm 10	92	0.15 \pm 0.03	0.19
2000	210	442 \pm 34	474	15.1 \pm 7.5	35.9	227 \pm 245	1020	0.34 \pm 0.31	0.90
2001	351	477 \pm 20	500	3.6 \pm 0.8	5.5	123 \pm 16	147	0.06	0.07
2000	178	504 \pm 42	569	5.2 \pm 2.3	13.0	99 \pm 38	171	0.21 \pm 0.04	0.29
1998	268	640 \pm 77	793	3.6 \pm 2.2	11.1	100 \pm 72	214	0.28 \pm 0.13	0.56
2003	129	706 \pm 78	855	3.2 \pm 2.2	10.6	78 \pm 27	114	0.18 \pm 0.04	0.25
2000	262	718 \pm 47	804	4.4 \pm 3.1	13.3	222 \pm 64	335	0.28 \pm 0.17	0.67
2003	302	993 \pm 305	1700	3.1 \pm 1.9	9.2	168 \pm 129	442	0.67 \pm 0.42	2.33

^aRanges given are the standard deviation in the values over the ICME event and do not include uncertainties in the measurement.

^bRatio of the number densities of the given elements

Table 2: CME Models

Year	Day	Input Parameters						Output Parameters			
		v_f km s ⁻¹	a km s ⁻²	v_i km s ⁻¹	ρ_e 10 ⁷ cm ⁻³	T_e 10 ⁶ K	$\frac{QE}{KE}$	ρ_{10R_\odot} 10 ³ cm ⁻³	charge states		
									O	Si	Fe
2002	173	425	0.1	10	10	1	0.7	10	6	7,8,6	8,9
2002	173	425	0.1	10	1	1	0	0.9	6	7,8,6	8,9,10
2000	210	500	0.1	20	10	2	5	30	7,6,8	12,11	16,17,15
2000	210	500	0.1	20	1	1.3	0	2.9	6	8,9,7	11,8,12,10,9
2001	351	500-800	0.1-0.25	10	5	1.8	6	7.0	6,7	12,11,10	14,15,13,16
2001	351	500-800	0.1-0.25	10	0.5	1.2	0	0.8	6	8,9,7	11,10,9,8
2000	178	500-850	0.1-0.15	10	10	1	9	15	6,7	10,11,12	16,15,17
2000	178	500-850	0.1-0.15	10	1	1	0	1.5	6	7,8,6	8,9,10
1998	268	750	0.1	15	10	2.3	8	16	7,8	12,11	16,17
1998	268	750	0.1	15	1	1	0	1.8	6	7,8	8,9,10
2003	129	700	0.1	10	10	1.2	2.6	11	6	9,10,8	13,12,14,15
2003	129	700	0.1	10	1	1.2	0	1.1	6	8,9,7	8,11,10,9
2000	262	700-900	0.1-0.15	15	10	2.5	3-2.5	17	7,8,6	12,11	16,15,14
2000	262	700-900	0.1-0.15	15	1	1.4	0	1.7	6	9,8,10	11,12,10,8
2003	302	1300-2500	0.2-1	20	10	2.3	4-8	15	7,8,6	12,11	16,17,15
2003	302	1300-2500	0.2-1	20	1	1.2	0	1.4	6	8,9,7	8,11,10,9

^aCharge states are listed in order of abundance composing a total charge fraction of at least 0.8.

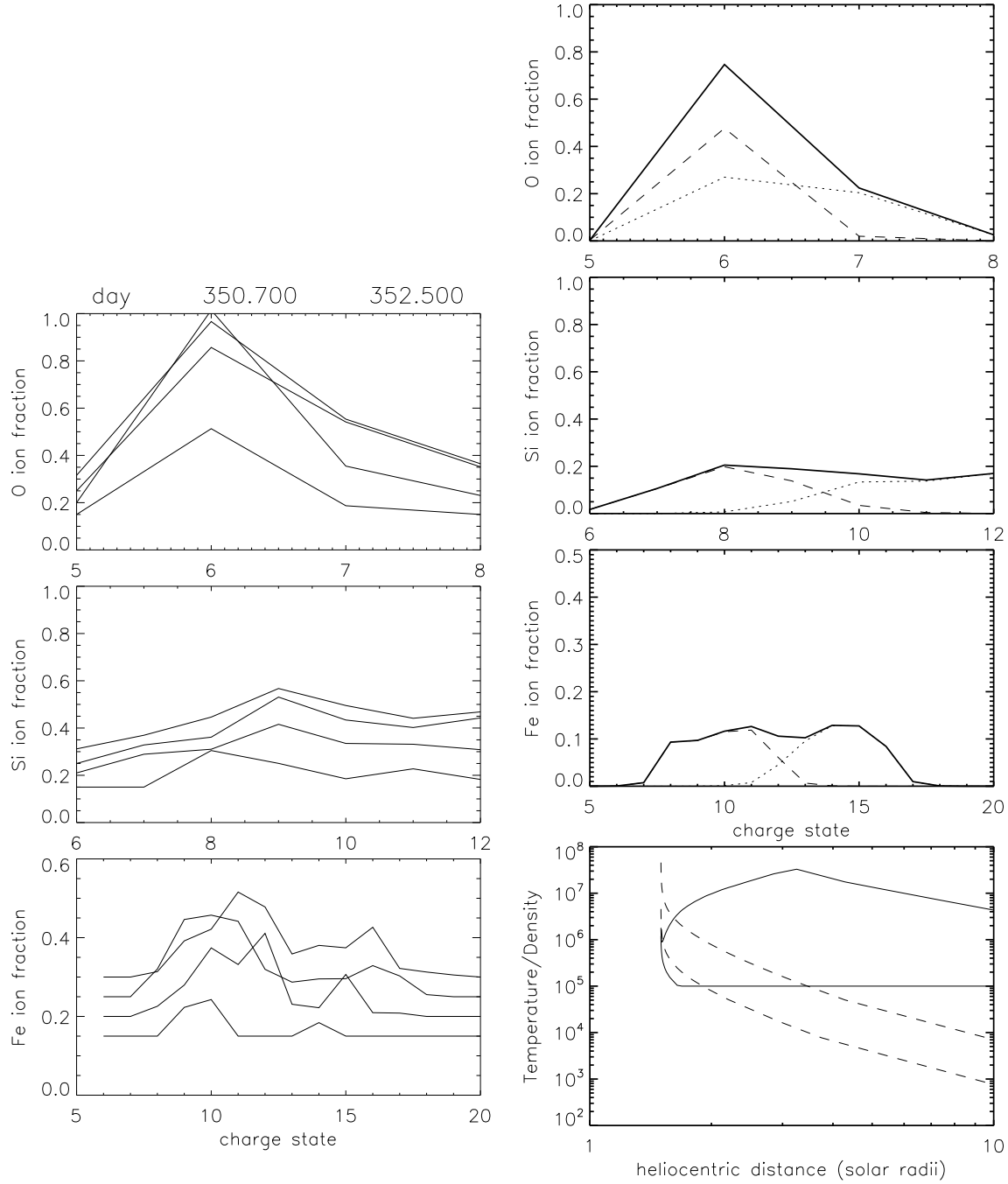


Fig. 1.— Charge state distributions for O, Si, and Fe given in terms of the ion fractions for the 2001 day 351 ICME. Plotted here are the ten hour average distributions, offset by increments of 0.05.

Fig. 2.— Model charge state distributions for the 2001 day 351 ICME for parameters given in Table 2 with weighting of [0.5,0.5] for the “core” and “cavity” components respectively. The bottom panel illustrates the temperature and density evolution close to the solar surface.

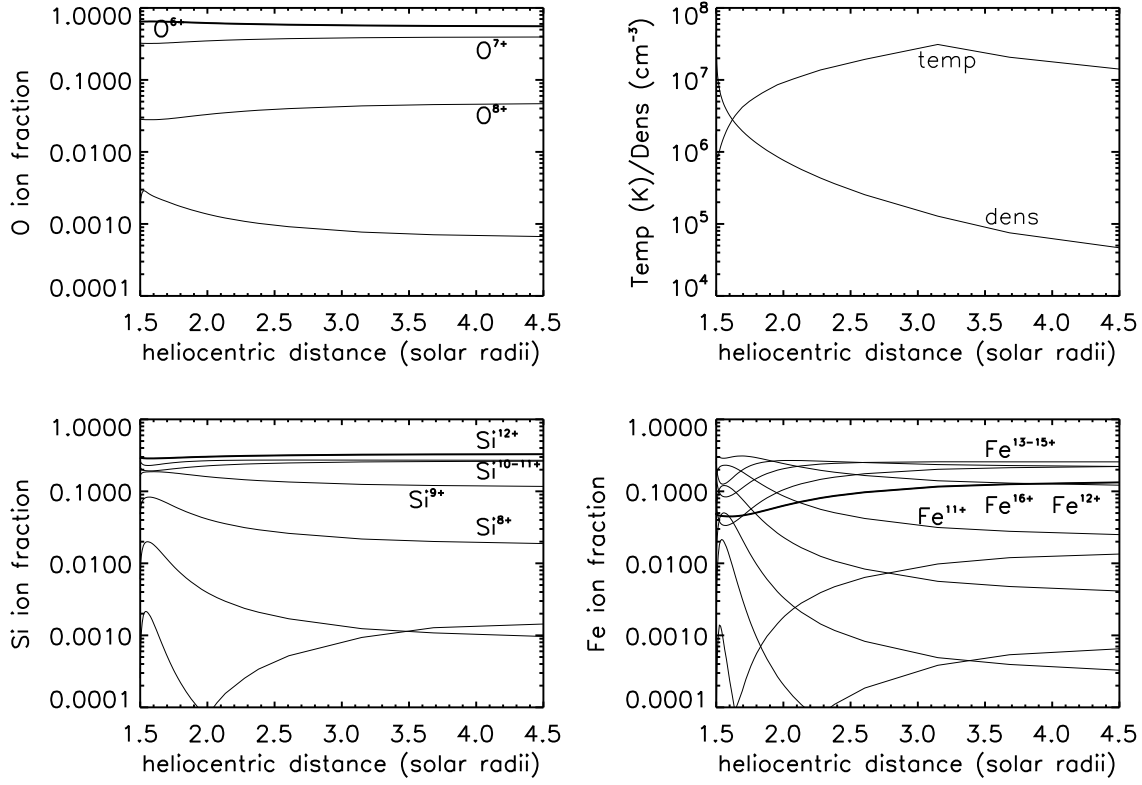


Fig. 3.— Evolution of charge state distributions for O, Si, and Fe for the 2001 day 351 “core” for parameters given in Table 2. The upper right panel illustrates the temperature and density evolution close to the solar surface.

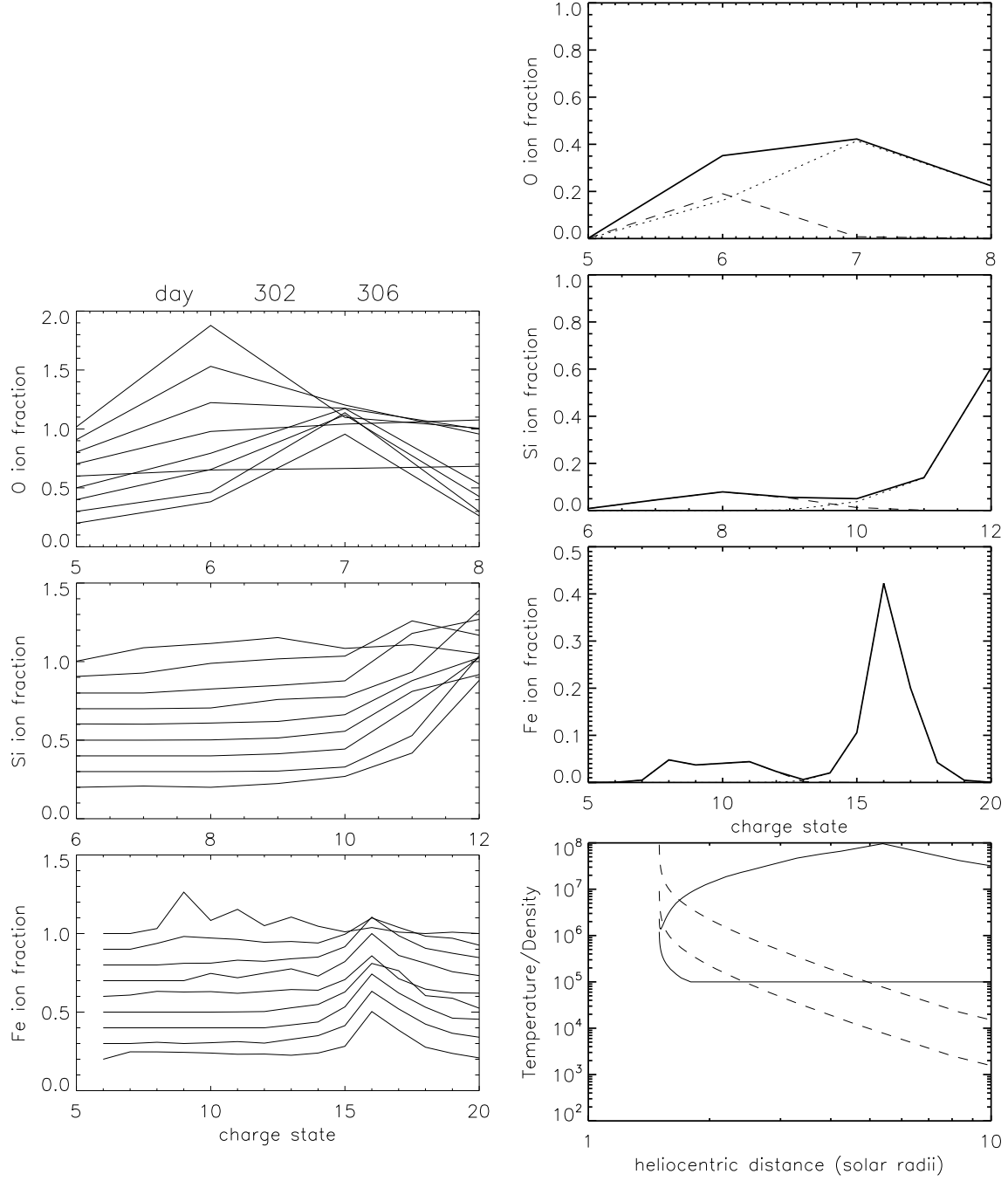


Fig. 4.— Same as figure 3 for ICME 2003 day 302. Increment between ten hour averages is 0.1

Fig. 5.— Same as figure 4 for ICME 2003 day 302, weighting [0.8,0.2] for the “core” and “cavity” contributions

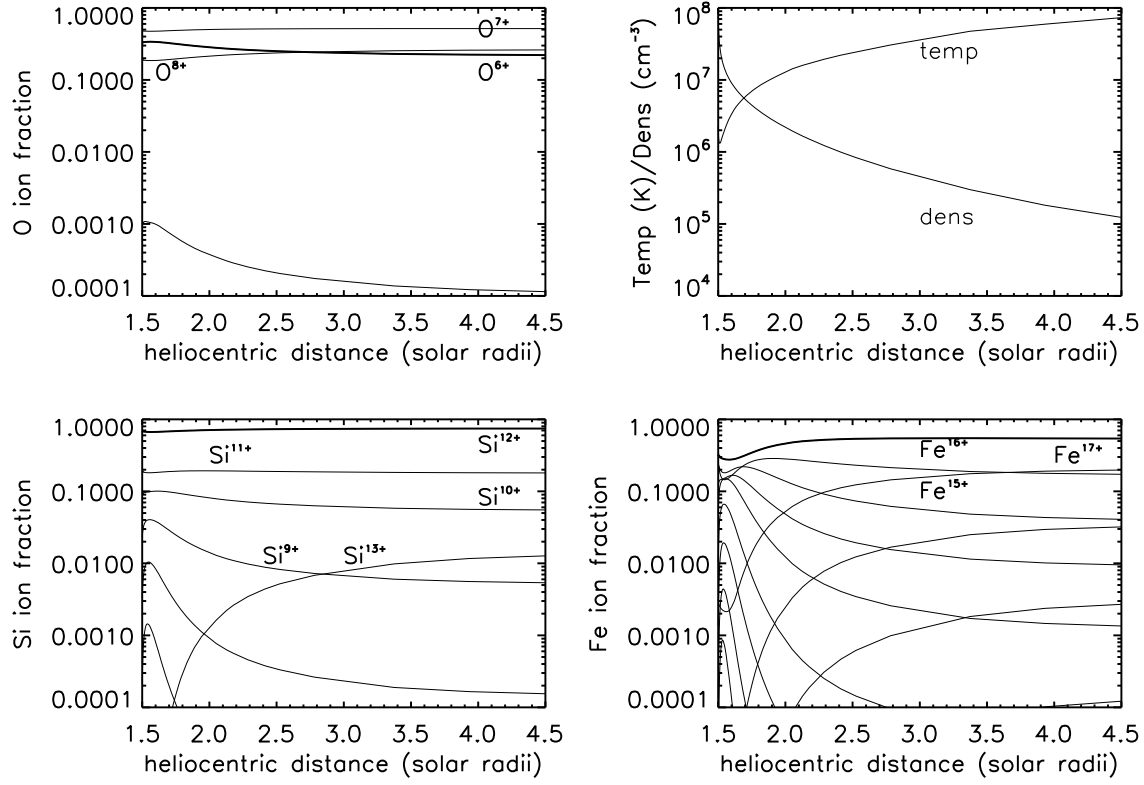


Fig. 6.— Evolution of charge state distributions for O, Si, and Fe for the 2003 day 302 “core” for parameters given in Table 2. The upper right panel illustrates the temperature and density evolution close to the solar surface.